SIMULTANEOUS SETTLEMENT OF INDO-PACIFIC EXTREMES?

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A Curious Coincidence

While the broad outlines of Polynesian prehistory are fairly well known, continuing surprises show that there is much be learned. Weisler (1998), for instance, found volcanic materials on Henderson Island which significantly pre-date the earliest known settlements on their source islands of Pitcairn and Mangareva. I want to lay the groundwork for what might be another surprise.

Given an interest in *moai*, and an interest in lemurs, one will eventually notice a curious coincidence: Madagascar and Rapa Nui – about the most widely separated islands one can reach by sailing in tropical waters – were both settled ca AD 500 by people originally hailing from Southeast Asia. (Africans themselves never made it to Madagascar.) The 18 tribes of Madagascar appear to have arrived as a result of 18 independent voyages, but whether these were single canoes or flotillas is unknown. Names for domestic animals are Kiswahili (indicating only that the voyagers did not take their livestock with them, but collected them from Africa at some point, which suggests that they knew of this possibility before sailing). Only one tribe stayed in Somalia long enough to pick up an appreciable number of African genes.

.There was an earlier people in Madagascar, the Vazimba, apparently also Malayo-Polynesian, who were displaced into the center by the new arrivals. The central forest was not burned out until about AD 1000, and the Vazimba are known in folklore as the guardians of the forest. Aside from that shadowy reputation, we know nothing of them except their tombs. Given the monsoonal wind reversals of the Indian Ocean, occasional bidirectional contact of Vazimbas with the homeland would have been possible, and would account for knowledge of the location of Madagascar in Indonesia in AD 500 .

Madagascar, extending for 1500 km north to south, lies athwart the latitude-sailing route, so it is hard to miss. The relative timing of the various arrivals is not known, but the distribution of tribal areas shown in Figure 1 leaves the impression of landings aimed at the center of the east coast, with perhaps some displacement of first arrivals inland by later arrivals.

Eighteen independent arrivals present no logistic or navigational problem, but unfortunately, Malagasy folklore appears to remember nothing helpful (although I confess that I have not exhausted the considerable ethnographic material in French). Nonetheless, all the tribes speak dialects of a common language, whose nearest relative is Bornean. This is to be compared with California (about the same size), in which 200 tribes spoke 200 mutually incomprehensible languages, indicating separate arrivals, a much longer habitation, or both.

Received wisdom holds that Rapa Nui was not reached directly from Southeast Asia, but by island hopping, with the last departure point somewhere much closer, such as the Marquesas or Pitcairn. Just for fun, I want to explore another possibility, which is that Rapa Nui was settled for the same reason that Madagascar was settled, and at about the same time. The computer modeling of Levison et al. (1973) suggested that the Pacific was settled intentionally rather than randomly, but a question remained about the reality of a pause between Western and Eastern Polynesia. Later modeling by Irwin et al. (1990) assumed a coherent philosophy of 3-way trips, in which exploration preceded colonization, so that many islands would be known, and probably visited, long before settlement. Irwin (1992) reports reasonable values for 'death at sea' of his model canoes, but

Figure 1. The tribal areas of Madagascar. While the distribution shows some effect of geography, the primary impression is one of central east-coast landings and displacement (after Bradt 1990:15).

he imposed 2 constraints on his models which probably inflate his failure rates. The minor constraint was that the canoes were not allowed to tack to hold a weatherly course, but it seems to me that any sailor who can safely negotiate a coral reef would long since have mastered tacking, even in an asymmetric boat.

The more important constraint was a 90-day limit on voyages. This might be generous if one had to carry all provisions, but MacIntyre et al. (1998) have already suggested that Polynesian ocean voyagers could live off the sea as they traveled. The limiting factor should not be food or water, but vitamin C; this deficiency, however, does not show up for 5 months. Such travel was possible for 3 reasons. Firstly, there were 10 to 30 times as many fish in the ocean before 1500 AD as there are now (MacIntyre et al. 1995), thanks to subsequent and ongoing extractive and unsustainable fishing practices. Secondly, fish appreciate anything which gives them a sense of place: even the cable mooring an oceanographic instrument in deep water will collect a community of organisms around it. Sessile organisms cling to it; fish seem to like to keep it in sight; sharks nibble it experimentally. A slowly moving boat – Irwin et al.'s (1990) model canoes ran at 4 knots (175 km/day) – will collect an entourage which swims with it. Steve Callahan (1999), adrift in an ill equipped raft in the Atlantic Equatorial Current, finally figured out how to cobble together a spear adequate to take dorados, and kept himself alive until he reached the Windward Islands nearly 11 weeks later. Thirdly, although I have not seen this recorded, it seems probable that Polynesians knew the trick of squeezing raw fish to provide a sort of drinkable gazpacho, replacing the need for fresh water. Thus there is no logistic impediment to a canoe of voyagers looking for a home in AD 500, and being directed ever onward, through Melanesia or Micronesia, through Polynesia, and, finally, finding Rapa Nui. There is no evidence to support such a non-stop emigration, which is simply the extreme case of a more logical sequence.

The Orang Laut, Moken, and Bajau are three unrelated groups with a common nomad-marine or 'sea gypsy' culture, still dwelling in outrigger houseboats in the Indonesian archipelago (Barnard 1996). Often stigmatized as pirates by landlubbers, the 3 groups did not compete for marine resources, but occupied different eco-niches, including some use of the land. Like the boat people who fled Vietnam during a more contemporary disaster, people living beside the sea, and of off it, tend to regard it as an escape route: 'their instinct is to flee – inevitably to the sea' (Magannon 1998).

The AD 535 Dark Sun Event destroyed at least 6 major Southeast Asian cultures, perhaps catastrophically, perhaps progressively in a series of cumulative misadventures. The socially peripheral 'sea gypsies' – perhaps most familiar to TV watchers as the floating population of Hong Kong's Victoria Harbor – were prepared by equipment and predilection to flee a disaster instantaneously. Is it possible that such people left Southeast Asia in sufficient numbers in 535 to form an outward emigration wave which was capable of displacing existing occupants of desirable real estate? Di Piazza and Pearthree (1999) recently suggested that the Lapita people, assumed to be ancestral Polynesians, were themselves sea gypsies traversing Melanesia along Kirch's (1997) route across the top of the Bismark-Sta Cruz-Vanuatu-Fiji arc. The Lapita, covering 4500 km in 3 to 5 centuries, performed 'the fastest known migration in prehistory', but if these islands were already occupied, the 535 contingent would not have stopped anywhere for very long. Curiously, of Polynesians so far sampled for mitochondrial DNA, only 5% have descended from a Melanesian mother (Sykes 2001: Chap. 6), suggesting that the Lapita kept very much to themselves during their journey.

The abandoned Polynesian islands suggest that Western Polynesian warfare eventually developed into an adequate population-control measure, so that there was no pressure to occupy marginal territory. Perhaps Rapa Nui was known, but there was no incentive to move there. An outward pulse in 535, however it was propagated, might have supplied the missing motivation. Oral tradition of the Rapanui describes their forefathers as escaping conflict; the lack of traditional colonization resources (at least dogs and pigs; Rapa Nui is too cool for breadfuit) supports a hasty and unplanned departure. With the 535 event driving an outward pulse, the Rapanui progenitors need not necessarily have departed from the logical nearest neighbors. They might have been at sea for some time, looking for a new home, but too few to invade, and directed ever eastward by existing populations. Even if Rapa Nui was still undiscovered, those who did not have a home to return to could keep sailing, supported by an optimism based on previous experience suggesting that sooner or later an island would turn up. (A 90-day continuous trip might cover 15,000 km.)

Boredom, rather than hunger, might be the major complaint. South America would then receive any canoes that failed to find an island, and a few strangers arriving on the west coast could be absorbed, or killed, without leaving a trace. (Yet at some point, New World sweet potatoes found their way out to the islands.)

WHAT HAPPENED IN 535 AD?

What we know directly comes from eyewitness accounts of consequences far from the action (collected by Keys 2000), and is little enough, but together these reports justify the name 'Dark Sun', and give us a foretaste of the 'nuclear winter' anticipated by Turco et al. (1983, 1990):

Zacharias of Mytilene (6^{th} century): 'the sun began to be darkened by day and the moon by night' (Hamilton and Brooks 1899).

John the Lydian (Byzantine historian writing sometime between AD 551 and AD 564): 'the sun became dim for nearly the whole year' (Wachsmuth 1897).

Procopius of Caesarea (in Palestine) [born ca AD 490/507- died ca AD 560]: 'the sun gave forth its light without brightness like the moon during the whole year' (Procopius 4.14.5).

Cassiodorus [Roman bureaucrat under Gothic emperors, born AD 484-490, died AD 584-590]: 'The sun ... seems to have lost its wonted light, and appears of a bluish colour. We marvel to see no shadows of our bodies at noon, to feel the mighty vigour of the sun's heat wasted into feebleness, and the phenomena which accompany an eclipse prolonged through almost a whole year. We have had ... a summer without heat ... the crops have been chilled by north winds ... the rain is denied ...' (O'Donnell 1979, Mommsen 1894).

John of Ephesus [earliest Syriac historian, born ca AD 505, died ca AD 585]: 'The sun became dark and its darkness lasted for 18 months. Each day it shone for about 4 hours, and still this light was only a feeble shadow ... the fruits did not ripen and the wine tasted like sour grapes'. The original is lost, but John was quoted by Michael the Syrian [Syrian Orthodox Patriarch, 1166-1199] (Chabot 1963).

We can deduce even from these telegraphic accounts that something a long way from the Mediterranean put dust or aerosol into the stratosphere, too tenuous to see, but capable of reflecting enough incoming energy to cool the Earth. There is evidence from many sources, both historical and in the mute (but noisy) record of tree rings, ice cores, and lake varves, for worldwide cooling in 535. Between cooling and shading, crops failed, leading to famine, cannibalism, and rebellion. Rainfall patterns changed, producing both droughts and floods. Plague, carried by rats spreading from African reservoirs, decimated urban centers in the Middle East. Demographic displacement from the Asian steppes brought barbarians to the Roman empire. Keys (2000) fills 8 chapters with such consequences, including the rise of Islam, and speaks of the 'resynchronizing' of history, much like restarting an auto race after a mass collision at the first corner.

This spring in Ireland has been a bit cool, dark, and damp – but having recently spent 5 years in Bergen, where moist air that has been over the relatively warm North Atlantic Drift suddenly climbs 600 m cliffs, anywhere else seems dry and sunny. Irish farmers make silage (plastic-wrapped hay preserved by anoxic fermentation, which need not be dried before wrapping) for winter feed, but grass growth has been so slow that silage harvested to date is a mere 10% of normal. Farmers are already talking with bankers, and warning that they will need government help to get through the winter. Tax income being down for other reasons, we have the makings of a local economic disaster from weather conditions that I had not even noticed. Irish historians suggest that the Christianization of Ireland was a consequence of the 535 event, after people lost faith in the old fertility gods when the crops failed. The climatic effects of stratospheric aerosol are complex, because the Mie (light-scattering) equations are highly non-linear in their dependence upon particle size, composition, and shape. Residence time depends upon the latitude and season of injection. The size of a sulfuric acid particle (volcanic emanation) depends upon the vapor pressure of water. Size matters because the incoming solar spectrum and the outgoing infrared spectrum are scattered differently. Theory suggests that while aerosols in general reflect solar energy away from the earth, if they are larger than 2.2 microns they may lead to net warming, because backscattered outgoing infrared radiation exceeds the loss of incoming energy (Hengeveld and Kertland 1995). In short, in the absence of constraining data, a skillful atmospheric modeler can produce nearly any climatic scenario you want from stratospheric particles. The possible sources of stratospheric aerosol are a major volcanic explosion, or a moderate cosmic strike. Since our experience with volcanoes is extensive, we will describe a known volcanic event first.

VULCANISM

If the 535 event was a volcanic explosion, it was larger than the well documented explosions of Krakatoa on 23 August 1883. These were heard 4800 km away at Rodriguez Island, near Mauritius. Barometers detected atmospheric shock waves circling the globe 3 times. The resulting tsunami, running in shallow water and impeded by complex topography, was 35 m high, destroyed 300 towns, killed 36,000 people, carried 600 ton coral blocks ashore, and deposited a Dutch warship 2.5 km inland. The explosion turned a 425 m island peak into a 275 m seabed (Decker and Decker 1981). Twenty km^3 of rock turned to volcanic dust in the atmosphere, reaching a height of 80 km and producing complete darkness for 2 days over a radius of 80 km. It was responsible for glorious sunsets around the world for the next 3 years – some of them spectacularly green. This type of eruption is called Plinian, after Pliny's description of Vesuvius: shallow premonitory earthquakes over a period of months, then deep earthquakes – indicative of magma rising by buoyancy through the crust – then an explosive eruption producing ignimbrites (ash particles so hot they weld together as they fall) and pumice (rock so full of gas vesicles that it floats on water). There are no lava flows. A Plinian eruption requires a hot fluid magma that is saturated with gas at pressures some distance below the surface; subducted seafloor with high water and carbonate contents is the customary starting material.

If enough magma escapes in the initial eruption, the enclosing shell of the volcano collapses into the magma chamber, creating a caldera. If this happens on an island, sea water floods the hole, the heat energy of the remaining magma converts water to steam, and the resulting 'phreatomagmatic' eruption can be many times more violent than the initial explosion. The sequence produces 2 explosions some hours apart, with the second one more violent.

There are several ways to measure the size of an eruption, of which the easiest is the intensity and magnitude pair.

Intensity ranges from 1 to 12 and is given by:

Intensity = $\log_{10}$ [mass-eruption-rate/(kg/s)] + 3

Magnitude ranges from 0 to 7 and is given by:

Magnitude = $\log_{10}$ (erupted-mass/kg) -7

These are most useful for volcanoes that remain in place after the eruption. Volcanoes that disappear, leaving a caldera, are another matter entirely, and are best measured on a less easily defined scale known as the Volcanic Explosivity Index, or VEI, also logarithmic, shown in Table 1. The VEI is composite and depends to some extent on the observations of survivors, if available.

Tambora, which seems to have been somewhat smaller than 535, produced the 'year without a summer'. Although it lowered the mean temperature of the northern hemisphere by only 0.4-0.7°C, it snowed every month of the year 1816 in New England (Stommel and Stommel 1979). Lamb's (1970) 'Dust Veil Index', which attempts to estimate the history of stratospheric dust concentrations, unfortunately does not extend back before 1500. Even the encyclopedic *Natural Climate Variability on Decade-to-Century Time Scales* (NRC 1995) knows nothing about 535. Still, there is a statistical association between volcanic activity and global temperatures over the last millennium (Hammer et al. 1980). The Medieval Climatic

Table 1. Volcanic Explosivity Index.
(from http://volcano.und.nodak.edu/vwdocs/eruption_scale.html)

VEI	Plume Height	Ejecta Volume	Type	Eruptions in last 10^4 years	Example
0	<100 m	10^3s m^3	Hawaiian	daily	Kilauea
1	<1 km	10^4s m^3	Hawaiian/ Strombolian	daily	Stromboli
2	1-5 km	10^6s m^3	Strombolian/ Vulcanian	3913	Galeras, 1922 Usu, 2000
3	3-15 km	10^7s m^3	Vulcanian	720	Ruiz, 1985 Lopevi, 2000
4	10-25 km	10^8s m^3	Vulcanian/ Plinian	131	Pelee, 1902 Rabaul, 1994
5	>25 km	1 km^3	Plinian	35	Vesuvius, AD 79 St. Helens, 1980
6	>25 km	10s km^3	Plinian/Ultra-Plinian	16	Thera, 1470 BC Krakatoa, 1883 Pinatubo, 1991 Katmai, 1912
7	>25 km	100s km^3	Ultra-Plinian	1	Tambora, 1815
8	>25 km	1000s km^3	Ultra-Plinian	0	Yellowstone

Optimum (1100-1250) was a period of low volcanism, while relatively high volcanism (1250-1500 and 1550-1700) occurs within the Little Ice Age.

There is so far no unequivocal scientific evidence for the nature of the 535 event. Keys examines 137 possible volcanoes, and makes a good case for an earlier and larger Krakatoan explosion being the culprit, but this is based entirely on circumstantial evidence. There is a dominant layer of pyroclastic material from a major explosion in Krakatoan ash deposits. Haraldur Sigurdsson's radiocarbon date from charcoal from 5 layers below this layer is 6600 BC, while the next layer above gives 1215-1300 AD. No charcoal was found in exposed sections of the pyroclastic layer, so it remains undated. The spanning dates permit a 535 explosion, but do not demand it, and do not even constrain it greatly; the problem is that no one has systematically excavated a trench looking for datable charcoal in the various layers. Krakatoa needs no motive, lacks an alibi, and certainly has the means, but may not have had the opportunity. One expects a massive young caldera in the Sunda Strait, and Keys offers 3 possible sites. With diameters between 30 and 55 km, these are all much larger than the 1883 caldera, which fits inside the islands of Verlaten, Lang, and the remainder of Krakatoa (Simkin and Fiske 1983). These islands appear to define an older 10-km caldera, possibly from the explosion which produced the thickest ash layer. Unfortunately, Keys presents no bathymetry to support the identification of these sites as possible calderas.

Although oceanography in the Sunda Strait is somewhat inhibited by the activity of pirates (Wang et al. 2000), recent work has shown that the Sunda Strait itself is not a caldera, but an extensional graben produced by stress associated with the differing behavior of the Indian plate as it disappears beneath Asia at 6 cm/year, uplifting the Himalayas, but subducting in Indonesia. This has the incidental effect of separating Sumatra from Java. Bathymetric imagery shows that deep spots in the graben are filled with several kilometers of sediment, dating from Oligocene to Pleistocene without disturbance (Lelgemann et al. 2000). Keys (2000) found a passage in the Chinese *Nan-shi* (*History of the Southern Dynasties*) which reports double thunder from the southwest, not associated with a storm, in 535. Krakatoa, however, is directly south of where the *Nan-shi* was written; the tip of India is southwest. This is a minor point, because low-frequency sound is hard to place, and atmospheric effects can displace distant noises.

Could it be that the 535 caldera was at the site of the 1883 caldera because volcanic regrowth had turned the old caldera into a new peak? Nea Kameni, in the caldera of Thera, has grown from a 700 m bottom in 3500 years (Antonopoulos 1992), compared to Anak Krakatoa's 275 m in 120 years, suggesting that Krakatoa refills faster than some explosive volcanoes. Still, the 1883 explosion follows rather too closely upon a giant 535 explosion. Krakatoa's recharge rate depends upon unknown subsurface dynamics, but with 2000 active volcanoes and fewer than 40 eruptions with VEI ~6 in the last 2 million years, it seems unlikely that Krakatoa could have produced 2 of them. (The tremendous lava volumes of flood basalts such as the Siberian and Deccan Traps – $2x10^6$ km^3 over a million-year period – are not subduction related, but the result of mantle plumes (White and McKenzie 1995)). Baillie (1994) pointed out that Greenland ice cores show no volcanic activity in 535, and suggested a cosmic strike.

The Cosmic Alternatives

The alternative to volcanism is a cosmic strike of some sort, by comet (a dirty snowball, flying gravel bank, or miscellaneous solid core surrounded by miscellaneous softer ices) or asteroid (a rock or a lump of nickel-iron). The possible variety of flying objects offers a variety of results. The book one wants is Clube and Napier (1997), *Catastrophes and Comets: The Destroyers of Cosmic Faith*; unfortunately, this book is still unpublished as I write. In its absence I have referred to the research papers of the authors. but the non-astronomical reader will probably find the book more generally informative.

The solar system oscillates through the galactic plane with a period near 33 million years (Rampino and Stothers 1986). When crossing this cluttered environment, the Oort cloud of comets – extending (by definition) halfway to the nearest stars – is disturbed, producing a 2-million-year pulse of large comets (50-100 km) that cross Earth orbit. These orbits take several paths: some are hyperbolic and leave after a single visit; others form long ellipses, from which they may eventually be deflected by Jupiter or Saturn and captured in chaotic orbits inside the orbit of Uranus. Five percent of these end up in relatively stable orbits in the 'cometary graveyard' inside the asteroid belt, called the 'Apollo-Amor-Aten (AAA) system', after 3 of its members. The cometary pulse dissipates with a half life of 5 million years; we currently appear to be about 10 million years into this process. Part of the dissipation is by the formation of tails, which are dust particles driven outward by photon pressure and the solar charged-particle wind. This material remains in interplanetary space and shows up as dust trail which eventually diffuse to produce the faint glow of zodiacal light. Another more emphatic form of dissipation is collision with planets, of which more below.

ASTEROID IMPACT

There are some 200 possible astroblemes (eroded asteroid impact sites) visible from satellites. At one time, the Earth was as peppered with astroblemes as the Moon is with craters, but plate tectonics, orogeny, and erosion have smoothed most of them. Still, asteroid impacts make up for their rarity by the severity of their consequences: the mass extinctions that mark the end of geological ages correspond unambiguously with the dates of the 25 largest astroblemes (Afanas'ev and Fel'dman 1996), and with the crossing of the galactic plane (Olano 2000). (Confusingly, flood basalts also correlate reasonably well with extinctions (Coffin and Eldholm 1994), although there is no conceivable connection between the two mechanisms.) The best known such strike was the KT (end of Cretaceous, beginning of Tertiary) event, responsible for the demise of the dinosaurs 65 million years ago. This was a 10-to-15-km nickel-iron asteroid which hit at Chicxulub in Yucatan (Pope et al. 1991, Hildebrand et al. 1991), creating a circular impact structure 300 km in diameter (Urrutia-Fucugauchi et al. 1996) containing characteristically shocked minerals, and leaving an iridium-rich layer nearly everywhere around the world. There is no other reasonable explanation of this layer (Alvarez et al. 1980), for iridium, a rare metal of the platinum group, is a sideropile which is selectively concentrated in the nickel-iron core of a planet during core formation.

The consequences of the KT impact were enormous, exterminating 70% of all biological families. In some places, rocks just below the boundary show a flora of 65 species; those above, 8 species. The conversion of kinetic energy to heat on impact explosively vaporizes a solid projectile and some of the receiving crust. (Only meteors small enough to be slowed by the atmosphere, and large enough to escape complete burn-up, make it to become collectible meteorites.) The KT impactor started worldwide fires, producing enough soot and dust to hide the sun for at least 6 months. By unlucky chance, Chicxulub was an evaporite basin containing anhydrite, a calcium sulphate, which when converted to a plasma in the presence of steam produces gaseous sulfuric acid. Sulfuric acid is hygroscopic and collects water forming a stratosphere aerosol. This reflected enough sunlight to reduced the surface temperature by an astonishing 3 to 10°C for several years. Fire, darkness, and cold between them killed large animals, many plants, and many primary consumers of photosynthesis (such as pelagic fish). Small animals, burrowers, birds, deepwater fish, and scavengers survived somewhat better. The KT event was considerably larger than the asteroids that are currently in Earth-crossing orbits. Keys (2000) suggests a that 4-km asteroid would have been adequate to produce the 535 event.

Some 60 known asteroids this size have Earth-crossing orbits, and one hits us every 50 million years or so. A difficulty with the asteroid hypothesis is that no modern crater is known on Indonesian land, or in shallow water, so the impact site would have been in the deep ocean, similar to an old 40 km crater off the coast of Nova Scotia now buried beneath 500 m of sediment. The resulting tsunami would have been far more impressive than a volcanic tsunami, and should have left traces, both geological and folkloric, around the edges of whatever ocean it hit. We seem to lack this sort of evidence. Also, Chicxulub to the contrary notwithstanding, an asteroid strike does not normally generate long-lasting sulfate aerosol. The only probable impact site in Southeast Asia seems to be Lake Tonle Sap in central Cambodia, which has been suggested as the source of the Australasian tektite (bits of silicate glass, aerodynamically shaped) strewn field (Hartung and Koeberl 1994), but this happened 0.77 million years ago (Claeys 1995).

COMETARY ENCOUNTER

Comets are fragile objects, and perihelion passage is hard on them. They degas and fracture, eventually forming a stream of large objects strung out along the orbit, (as we saw with Shoemaker-Levy 9) surrounded by an equal mass of gravel, fine dust, and gas. Orbital resonances with Jupiter are a lively research topic at the moment (Koon et al. 2001), and seem to be what stretches cometary material along the orbit (Clube and Napier 1987). This slowly expanding stream continues to orbit the sun; when the Earth passes through an old depleted stream, the gravel produces a meteor shower. The best known shower impact was on 12 February 1947 at Sikhote-Alin, north of Vladivostok. This was apparently a compact but unconsolidated object of some 100 tons when it hit the atmosphere, which broke up at an altitude of 4.5 km and peppered a 5 by 15 km ellipse with iron meteorites (some 8000 of which have been collected, one weighing 1.8 tons), and sounding like at artillery barrage in the process (Gallant 19). The iron suggests that this was an asteroid; the aerial breakup is more characteristic of a comet, but the discoveries of asteroids with moons (Merline et al. 1999), and boulders on the surface (Thomas et al. 2001), suggests that asteroids need not be monolithic, and "stony-irons" contain both iron and gravel.

When the Earth passes through a young stream, avoiding collision with the major members, enough fine dust may enter the stratosphere to trigger an ice age. Close passage to the main body may result in fragmentation. Clube and Napier (1984) suggest from orbital calculations (Steel et al. 1991) that some 20,000 years ago, a large (50-100 km) comet entered the AAA system and disintegrated in 3 major episodes in 2800 BC, 1000 BC, and 500 AD, forming, in the process: Encke's comet (3.30-year period), the Taurid (July) meteor stream, episodes of enhanced zodiacal light (apparently confused with the Milky Way by early observers), a piece which hit the moon in 1178, the Tunguska fireball of 1908, a number of 1-km objects (Asher et al. 1993), a fireball swarm in 1951, and a series of boulder-sized lunar impacts in 1975. Possibly relevant to our discussion, a major bit of the ca. AD 500 disintegration is so far unaccounted for (Clube and Asher 1990).

The spectacular impacts of Shoemaker-Levy 9 on Jupiter were a high point of 1994 astronomy, and offer a convincing demonstration of the possibility of cometery strikes. The minor blips seen on Jupiter would have wiped out human civilization had they hit the Earth. A comet strike in the Indian Ocean would not leave a crater, nor would it generate much sulfuric acid, which is the usual aerosol found in the stratosphere. However, the eruptions of El Chichón since 1982 have shown that NaCl can form an important part of volcanic aerosol (Woods et al. 1985), suggesting that NaCl aerosol may have made some contribution to the climatic effects of earlier eruptions. Not yet available is an estimate of the aerosol that might be produced by a cometary marine strike. Even the gentle evaporation of seawater is a complex process which can produce some 200 different salts and hydrates, and the required foundation of kinetic and thermodynamic data, even at ordinary temperatures, does not yet exist. Contemporary modeling of the chemistry of volcanic aerosols is limited to known gas-particle reactions (Fridlind and Jacobson 2000).

Table 2. Alternatives for the 535 event.

Event	Stratospheric aerosol	Site mark	Advance warning
Volcano	Usual	Caldera	Earthquake
Asteroid	Marine strike	Crater	None
Comet	Marine strike	Perhaps none	Low end-on visibility

Light scattering by small particles can be very low in the backward direction for transparent objects, so the view of an incoming comet on a collision course may show only a small and inconspicuous blur, no more noticeable than an approaching asteroid in pre-telescopic days, and thus unlikely to be recorded in historical sources. Table 2 suggests some differences in the 3 candidates for the 535 event. We have considered only 1 volcano: Keys looked at 173 and thought Krakatoa the most likely, but as noted, the "refilling time" seems too short. Alternative sites have not been entirely ruled out. The lack of an asteroid impact site on land, and the lack of evidence for a major tsunami, argue against a solid impactor. A cometary marine strike seems most likely, with the absence of a comet from the usually observant Chinese a result of a low-visibility head-on approach.

INDONESIAN AFFAIRS

The sequels of the 535 event in the West include plagues, famines, barbarian irruptions, collapse of empires, and religious upheavals. Another less noticeable, but perhaps more important consequence was that Justinian, in the hope of appeasing an angry deity by shutting down a source of contentious debate, fired the last pagan teachers from Plato's Academy. He thus inadvertently helped to usher in the 800 years of intellectual stagnation which we call the Dark Ages. With so much to answer for far from the source, it would be surprising if the 535 event had not had some effect on Indonesia. While there is little direct record of anything happening, this may simply mean that the event destroyed the infrastructure required for the recording of history. The indefatigable Keys did turn up a written account from Indonesia. This is from the Javanese *Pustaka Raja Purwa* (*Book of Ancent Kings*), and after some preliminary description which would fit any major eruption it adds the remarkable passage (Keys 2000:387):

> At last, the mountain burst into pieces with a tremendous roar and sank into the deepest of the earth. The water of the sea rose and inundated the land. The land became sea and the island [of Java/Sumatra] divided into two parts.

This reads like an eyewitness account of an extraordinary phreatomagmatic explosion creating the Sunda Strait, but the major consequence of this report is to muddy the waters. The problems lie in the reliability of the source, the absence of any solid evidence of a 535 explosion, the sediments in the Sunda-graben, the internal dating of this event to the year 416, more than a century too early, and the fact that the Strait is a geologically old tensional graben rather than a historical caldera. These problems are not necessarily fatal. Hyperbole is the usual companion of disaster. The earliest extant copy of the *Pustaka* is a manuscript from 1869. Copyists have been known to get dates wrong by far more than this, and reasonable descriptions of other eruptions have survived centuries of oral transmission. On the other hand, Indonesia has no dearth of volcanoes, whose eruptions could have colored the phraseology of copyists down the millennia.

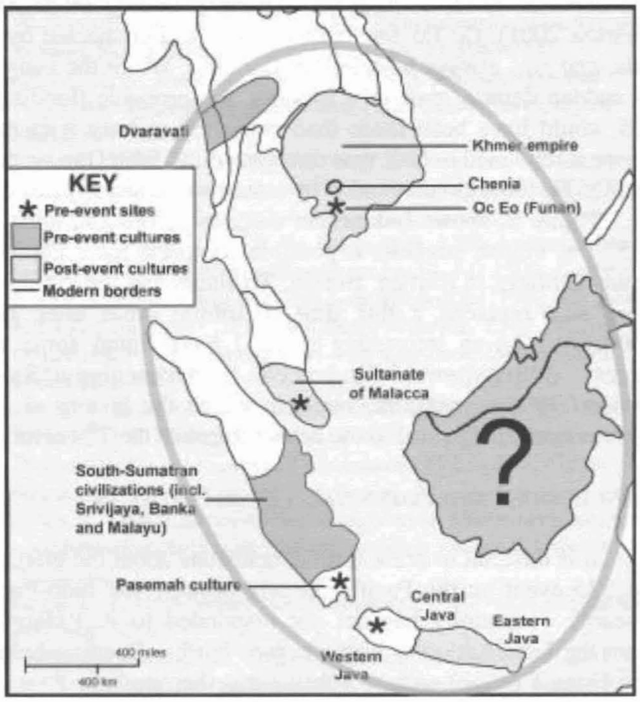

Figure 2. Indonesian cultures before and after 535 AD. The ellipse suggests a possible footprint for a cometary strike. Cultures in Borneo, Burma, Thailand, and the Phillipines were also replaced at this time (Cultural areas after Keys 2000).

CULTURES VANISHED

Figure 2 incorporates a map from Keys that shows discontinuities in Southeast Asian cultures. The chances are good that this map is incomplete and could be extended to show additional disruptions. One of the vanished cultures will serve to indicate just how much there is to be explained here. Oc Eo was the maritime capital of the Kingdom of Funan (Phu Nam) in Cambodia and south Vietnam from the 1st to 6th centuries, cultivating rice, beans, and cotton, raising pigs, sheep, and elephants, and worshipping Hindu gods. Situated in the Mekong Delta, the city had trade links with Rome, Greece, Persia, India, Burma and China. Exports included cotton, silk, sandalwood, rhinoceros horn, parrots, gold, silver, bronze, copper, lapis lazuli, mother-of-pearl, jewelry, ivory, and crystal and colored glass. Complex 'Indo-Pacific' glass beads (like those made in Venice a millennium later) were made by an ancient Indian process similar to one patented by the Libby Glass Co. in 1917, and exported to all of Asia and Africa, including Madagascar (Francis 2001). Oc Eo was built on piles and connected by canals, and was always troubled by flooding. While the cause of its sudden demise remains a mystery, the probable flooding of 535 would have been more than sufficient to bury it in mud, where it remained until it was discovered in 1940. One suspects that Oc Eo too was surrounded by a nimbus of 'sea gypsies'.

Figure 2. shows Indonesian cultures before and after AD 535. The ellipse suggests a possible footprint for a cometary strike. Cultures in Borneo, Burma, Thailand, and the Phillipines were also replaced a this time. (Cultural areas after Keys 2000:390.) As an interesting aside, I have found some web pages (http://wwwehltflinders.edu.au/Archaeology/*Smith/Gender/ 1998/horne/quotes.html) in which the history of Java ignores everything prior to the new cultures of the 7th century.

Conclusions and Potential Thesis Projects

It is difficult to draw solid conclusions about the effects of the 535 event on the Pacific, largely because the Indo-Pacific research community has not yet responded to it. References from the Late Antiquity web site (see Further Reading below), and Gunn's (2000) collection bring together studies of Europe, Africa, Asia, and MesoAmerica, but little from the Indo-Pacific. Given the high probability that the event was centered in Southeast Asia, this seems a bit remiss. There is a curious and arbitrary division between 'Asia' and 'Pacific' in some disciplines, which runs the boundary vertically between Irian Jaya and Papua-New Guinea. Is it the case that this imaginary line has taken on more reality than it should? I am not qualified to enter the minefield of debate about who settled what, when, from whence in Eastern Polynesia, but merely want to add the high probability of an outward push from Southeast Asia in AD 535, whose effects were felt westward as far as Rapa Nui is eastward.

With respect to the settlement of Rapa Nui, I do not mean to disparage the early radiocarbon dating when I say that it would be desirable to redo it. Please read this comment as support for research funding to bring modern methods to bear on the problem, and not as a criticism of early work. Beta counting is a very crude tool compared to mass spectrometric isotope analysis, and (as a quondam beta-counter myself) I am not truly happy with any of the dates I have seen, so I am reluctant to base any strong conclusions on them. Dating is important because the hypothesis of a 535-related settlement of Rapa Nui could easily be falsified by a firm occupancy date (as distinguished from an exploratory visit) of AD 400 , or a first-arrival date of AD 650 .

There is surely charcoal somewhere in the pyroclastic layer of the Krakatoa ash. Dating this layer (and others) is a project which could be solved merely by throwing money at it. There are several others avenues which might also be explored. People acquainted with Polynesian, Indonesian, and Malagasy languages they tell me that no one has had reason to make linguistic comparisons between the end members of this sequence. A glottochronological analysis of the relations among the languages of Borneo, Polynesia and Madagascar would be of some interest. However, the magnitude of a thorough investigation of such linguistic links should be considered by any prospective graduate student: as counted by "splitters", there are 726 living languages in Indonesia (which includes the larger part of Borneo), 139 in Malaysia (whose provinces Sabah and Sarawak are in Borneo), and 17 in Brunei (a small enclave on Borneo) (SIL 2002).

The Indo-Pacific beads found in Madagascar have not been analyzed for date and provenance. This needs doing! Keys's research, however thorough for the author of a broad view of history, suggests additional areas for serious digging by specialists. A critical study of the *Pustaka Raja Purwa* would not be out of order. There might well be more information than Keys (2000) dug up, and every manuscript has more to reveal than appears on the surface. It would also be of interest to look for 535-related cultural change over a broader area, particularly toward India. The question of what happened on Borneo seems wide open.

Finally, it might be possible to see if orbital dynamics allows the missing piece from the ca AD 500 breakup of the Encke progenitor to hit the Earth in 535. Did the 535 event occur near the end of June? Does the *Nan-shi* mention this? A questions for physical chemists: starting from a seawater plasma at ground zero, cooling adiabatically as it rises to the stratosphere, what is the expected size, shape, and composition of the resulting stratospheric aerosol? And finally, a question for optical physicists: The blue coloration of the sun mentioned by Cassiodorus tells us something about the aerosol responsible. (There have been related episodes of blue moons – not to be confused with "cylindrical 'blue moons'", which have, by a comedy of errors, lately become particular choices for the 13th lunation in a solar year (see Olson et al. 1999), but rare instances of the moon appearing blue – after Krakatoa in 1883, and in Newfoundland after forest fires in 1951.) Light-scattering calculations deal with increasingly complex particles as computers become more powerful. Spheres are now easy, but what are the chances of useful results from cubical aerosols?

References

Afanas'ev, S., L. and V. I. Fel'dman 1996. Astroblemes and the Beginnings of Geologic Ages. *Solar System Research* 30:28-30.

Alvarez, L.W., W. Alvarez, F. Asaro and H.V. Michel 1980. Extraterrestrial cause of the Cretaceous-Tertiary extinction, *Science* 208:1095-1108.

Antonopoulos, J. 1992. The great eruption of Thera volcano and the ensuing tsunami in the Greek Archipelago. *Natural Hazards*

(#2):153-168.

Asher, D. J., S. V. M. Clube and D. I. Steel 1993. Asteroids in the Taurid complex. *Mon. Not. Roy. Astr. Soc.* 264:93-105.

Baillie, M. G. L. 1994. Dendrochronology Raises Questions about the Nature of the AD 536 Dust-veil Event. *The Holocene* 4:212-217.

Barnard, T. P. 1996. Riau in Transition: The Globalization of a Peripheral Region in Indonesia. *International Institute for Asian Studies Newsletter* 7: 62-63.

Bradt, H. 1990. *Guide to Madagascar*, 2nd ed.. Bradt Publications, Chalfont St Peter, Bucks, England. (Look for an updated version if you head for the island).

Callahan, S. 1999. *Adrift: Seventy Six Days Lost at Sea*. New York: Adventure Library.

Chabot, J.-B. 1963. *Chronique de Michel le Syrien.* Paris: E. Leroux, 1899; repr. Bruxelles: Culture et Civilisation.

Claeys, P. 1995. When the sky fell on our heads: Identification and interpretation of impact products in the sedimentary record. *Rev. Geophys.* 35:Suppl.

Clube, S. V. M. and D. J. Asher 1990. *Asteroids, Cometes, Meteors III.* C.-I. Lagerkvist, H. Rickman, B. A. Lindblat and M. Lindgren eds. :275 Sweden: University of Uppsala Press.

Clube, S. V. M. and W. M. N. Napier 1984. The microstructure of terrestrial catastrophism. *Mon. Not. Roy. Astr. Soc.* 211:953-968.

Clube, S. V. M. and W. M. Napier 1987. The cometary breakup hypothesis re-examined – A reply. *Mon. Not. Roy. Astr. Soc.* 225:55P-58P.

Clube, S. V. M. and W. M. N. Napier 1997. Catastrophes and Comets: The Destroyers of Cosmic Faith. *World Scientific Series in Astronomy and Astrophysics* 3.

Coffin, M. F. and O. Eldholm 1994. Large igneous provinces: Crustal structure, dimensions, and external consequences. *Reviews of Geophysics* **32**:1-36.

Decker, R. and B. Decker. 1981. The Eruption of Mount St. Helens. *Scientific American* 244 (3):68-80.

Di Piazza, A. and E. Pearthree 1999. The Spread of the Lapita People: A Demographic Simulation. *Journal Artificial Societies and Social Simulation* 2(#3), http://www.soc.surrey.ac.uk/JASSS/2/3/4.html

Francis, P. Jr 2001. *Asia's Maritime Bead Trade from ca. 300 BC to the Present.* Honolulu: University of Hawai'i Press.

Fridlind, A. M. and M. Z. Jacobson 2000. A study of gas-aerosol equilibrium and aerosol pH in the remote marine boundary layer during the First Aerosol Characterization Experiment (ACE1). *J. Geophys. Res.* 105:17, 325-17,340.

Gallant, R. A. 2002. *Sikhote-Alin Revisited.* To the best of my knowledge this paper appears only on the web site of the Southworth Planetarium of University of Southerm Maine, at www.usm.maine.edu/~planet /galbtxt.html.

Gunn, J. D., ed. 2000. *The Years without Summer: Tracing AD 536 and its Aftermath.* BAR International Series 872, Oxford: Archaeopress.

Hamilton, F. J. and E. W. Brooks 1899. *Chronicle of Zacharias of Mytilene.* London.

Hammer, C. U., H. B. Clausen, and W. Dansgaard 1980. Greenland ice sheet evidence of post-glacial volcanism and its climatic impact. *Nature* 288:230-235.

Hartung J. B., and C. Koeberl 1994. In search of the Australasian tektite source crater: The Tonle Sap hypothesis. *Meteoritics* 29:411-416.

Hildebrand, A. R., G. T. Penfield, D. Kring, M. Pilkington, A. Camargo Z., S. B. Jacobsen, and W. Boynton 1991. Chicxulub crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatan peninsula, Mexico, *Geology* 19:867-871.

Hengeveld, H. and P. Kertland 1995. An assessment of new developments relevant to the science of climate change. *Climate Change Newsletter* 7, August, 24p. Available from the Australian Bureau of Resource Sciences, Canberra.

Irwin, G. 1992. *The Prehistoric Exploration and Colonisation of the Pacific.* Cambridge: Cambridge University Press.

Irwin, G. J., S. H. Buckler and P. Quirke 1990. Voyaging by canoe and computer: experiments in the settlement of the Pacific. *Antiquity* 64:34-50.

Keys, D. 2000. *Catastrophe*. London: Arrow. (Keyes is the principal sleuth of the 535 event).

Kirch, P. V. 1997. *The Lapita Peoples. Ancestors of the Oceanic World.* Oxford: Blackwell Publishers.

Koon, W. S., M. W. Lo, J. E. Marsden and S. D. Ross 2001. Resonance and capture of Jupiter comets. *Celestial Mechanics and Dynamical Astronomy* 81:27–38.

Lamb, H. H. 1970. Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance. *Phil. Trans. Roy. Soc. London* A266:425-533.

Lelgemann (now Kopp), H., M. -A. Gutscher, J. Bialas, E. R. Flueh, W. Weinrebe, and C. Reichert 2000. T Granstensional bain in the Western Sunda Strait. *Geophys. Res. Lett.* 27:3545-3548.

Levison, M., R. G. Ward and J. W. Webb 1973. *The Settlement of Polynesia: A Computer Simulation.* Ann Harbor:University of Michigan Press.

MacIntyre, F., K. W. Estep, and T. T. Noji 1995. Is it *deforestation* or *desertification* when we do it to the ocean? *NAGA, The ICLARM Quarterly* 18(3):4-6.

MacIntyre, F., T. T. Noji and K. W. Estep 1998. Shifts in marine biomass and the provisioning of voyages before AD 1500. *Easter Island in Pacific Context, South Seas Symposium. Proc. 4th Internat. Conf. on Easter Island and East Polynesia*, C. M. Stevenson, G. Lee and F. J. Morin eds. :107-112. Los Osos: Easter Island Foundation.

Merline, W. J., L. M. Close, C. Dumas, C. R. Chapman, F. Roddier, F. Menard, D. C. Slater, G. Duvert, C. Shelton and T. Morgan 1999. Discovery of a moon orbiting the asteroid 45 Eugenia. *Nature* 401:565.

Mommsen, T. 1894. Cassiodori Senatoris Variae, *Monumenta Germaniae Historica, Auctorum Antiquissimorum Tomus* XII, Berlin: Weidmann.

Magannon, E. T. 1998. Where the spirits roam. *The UNESCO Courier* July/Aug: 62-63.

NRC (National Research Council) 1995. *Natural Climate Variability on Decade-to-Century Time Scales.* Washington DC: National Academy Press.

O'Donnell, J. J. 1979. *Cassiodorus.* Berkeley: University of California Press.

Olano, C. A. 2000. The solar system linked to a gigantic interstellar cloud, during 500 myr: implications for a galactic theory of terrestrial catastrophism. *Instituto Argentino de Radioastronomía*. Paper presented at the Catastrophic Events Conference Vienna, 9-12 July 2000.

Olson, D. W., R. T. Fienberg, and R. W. Sinnott 1999. What's a Blue Moon? *Sky and Telescope*, May:36-38.

Pope, K. O., A. C. Ocampo, and C. E. Duller 1991. Mexican site for the K/T impact crater? *Nature* 351:105.

Procopius of Caesarea (6th century) *Wars*. Transl. H. B Dewing. (Loeb Classical Library, Harvard).

Rampino, M. R., and R. B. Stothers 1986. Geologic periodicities and the Galaxy. *The Galaxy and the Solar System*, R. Smoluchowski, J. N. Bahcall, and M. S. Matthews, eds. :241-259. University of Arizona Press.

SSP (Shipboard Scientific Party College Station TX Ocean Drilling Program 2000. Leg 184 summary: exploring the Asian monsoon through drilling in the South China Sea. Wang, P., W. L. Prell, P. Blum. *Proc. ODP, Init. Repts* 184:1-77.

SIL (Summer Institute of Languages) 2002. http://www.ethnologue.com/show_country.asp?name=Indonesia.

Simkin, T. and R. S. Fiske 1983. *Krakatau 1883: The Volcanic Eruption and Its Effects.* Washington DC: Smithsonian Institute.

Steel, D. I., D. J. Asher and S. V. M. Clube 1991. The structure and evolution of the Taurid complex. *Mon. Not. Roy. Astr. Soc.* 251:633-648.

Stommel, H. and E. Stommel 1979. The Year Without a Summer. *Scientific American* 240:176-186.

Sykes, B. 2001. *The Seven Daughters of Eve.* London: Corgi.

Thomas, P. C., J. Veverka, M. S. Robinson and S. Murchie 2001. Shoemaker crater as the source of most ejecta blocks on the asteroid 433 Eros. *Nature* 413:394-396.

Turco, R. P., O. B. Toon, T. P. Ackerman, J. B. Pollack and C. Sagan 1983. [TTAPS] Nuclear Winter: Global Consequences of Multiple Nuclear Explosions, *Science* 222:1283-1297.

Turco, R. P., O. B. Toon, T. P. Ackerman, J. B. Pollack and C. Sagan. 1990. [TTAPS II] Climate and Smoke: An Appraisal of Nuclear Winter *Science* 247:166-176.

Urrutia-Fucugauchi J., L. Marin and A. Trejo-Garcia 1996. UNAM Scientific drilling program of Chicxulub impact structure – Evidence for a 300 kilometer crater diameter. *Geophysical Research Letters* 23:1565-1568.

Wachsmuth, C. 1897. *Ioannis Laurentii Lydi liber de ostentis et calendaria graeca omnia.* Leipzig.

Weisler, M. I. 1998. Issues in the colonisation and settlement of Polynesian islands. *Proceedings of the Second International Congress on Easter Island and East Polynesian*

Prehistory, P. Vargas, ed. :79-84. Santiago: Easter Island Studies Institute, FAU, University of Chile.

Wang, P., W.L. Prell, P. Blum, et al., 2000. Proc. ODP, Init. Repts, 184. Shipboard Scientific Party. College Station, Texas (Ocean Drilling Program), 1-77.

White, R. S. and D. McKenzie 1995. Mantle plumes and flood basalts. *Journal of Geophysical Research* 100:17,543-17,585.

Woods, D. C., R. L. Chuan and W. I. Rose 1985. Halite particles injected into the stratosphere by the 1982 El Chichón eruption. *Science* 230:170-172.

Further Reading

Baillie, M. G. L. 1995. Patrick, Comets, and Christianity. *Emania* 13:69-78.

Berry, W. E. 1987. Southern Burgundy in Late Antiquity and the Middle Ages. *Regional Dynamics: Burgundian Landscapes in Historical Perspective.* C. Crumley and M. Marquardt eds. :447-609, Orlando: Academic Press.

Birdsell, J. B. 1973. A Basic Demographic Unit. *Current Anthropology* 4:337-356.

Broecker, W. S. 1995. Chaotic Climate. *Scientific American* 273:62-69.

Bryson, R. A. 1988. Civilization and Rapid Climate Change. *Environmental Conservation* 15:7-15.

Bryson, R. A. 1994. Orbital History, Volcanism, and Major Climate Changes: On Integrating Climate Change and Culture Change. *Human Ecology* 22:115-158.

Bryson, R. A. and T. J. Murray 1977. *Climates Of Hunger: Mankind And The World's Changing Weather.* Madison: The University of Wisconsin Press.

Bryson, R. A. and B. M. Goodman 1980. Volcanic Activity and Climatic Changes. *Science* 207:1041-1044.

Denton, G. and K. Wibjorn 1973. Holocene Climatic Variations-Their Pattern and Possible Cause. *Quaternary Research* 3:155-205.

Faul H. 1966. Tektites are terrestrial. *Science* 152:1341-1345.

Folan, W. J., J. Gunn, J. D. Eaton, and R. W. Patch 1983. Paleoclimatological Patterning in Southern Mesoamerica. *J. Field Archaeology* 10:453-468.

Gill, R. B. 1994. *The Great Maya Droughts.* Unpublished Dissertation, Austin: The University of Texas.

Gribbin, J. and M. Gribbin 1997. *Fire on Earth.* New York: St. Martin's Griffin.

Gunn, J. 1994. Global Climate and Regional Biocultural Diversity. *Historical Ecology*, Carole L. Crumley ed. :67-97. School of American Research, Santa Fe.

Gunn, J. D. 1997. A Framework for the Middle-Late Holocene Transition: Astronomical and Geophysical Conditions. *Southeastern Archaeologist* 16:134-151.

Gunn, J. D. and R. E. W. Adams 1981. Climatic Change, Culture, and Civilization in North America. *World Archaeology* 13:85-100.

Gunn, J., W. Folan and H. Robichaux 1995. A Landscape Analysis of the Candelaria Watershed in Mexico: Insights into Paleoclimates Affecting Upland Horticulture in the Southern Yucatan Peninsula Semi-Karst. *Geoarchaeology: An International Journal* 10:3-42.

Kauffman, S. 1995. *At Home in the Universe: The Search for Laws of Self-Organization and Complexity.* New York: Oxford University Press.

Lamb, H. H. 1977. *Climate: Present, Past and Future: Climatic History and the Future.* Vol 2, London: Methuen and Co.

Ladurie, E. L. 1971. *Times of Feast, Times of Famine: A History of Climate Since the Year 1000.* Translated by B. Bray. New York: Doubleday.

Lovelock, J. 1989. Geophysiology. *Trans. Roy. Soc. Edinburgh: Earth Sciences* 80:169-175.

Murdock, G. P. and D. R. White 1968. Cross-Cultural Sample. *Ethnology* 8:329-369.

Nan-shi, History of the Southern Dynasties (Song, Liang and Chen: AD 420-589), written by Li Yan-shou of Tang during the period AD 627-649.

Pustaka Raja Purwa (The Book of Ancient Kings) This is a manuscript in the Sasana Pustaka Library of the Karaton (Royal Palace) Surukarta in central Java. Keys had the relevant paragraphs translated.

Rao, J. 1996. The Leonids' Last Hurrah? *Sky and Telescope* 11:74.

Rasmussen, K. L., H. B. Clausen and G. W. Kallemeyn 1995. No Iridium Anomaly after the 1908 Tunguska Impact: Evidence from a Greenland Ice Core. *Meteoritics* 30:634-638.

Simkin, T. and L. Siebert 1994. *Volcanoes of the World.* Washington DC: Smithsonian Inst. Press.

Stothers, R. B. 1984. Mystery cloud of AD 536. *Nature* 307:344-345.

Wendland, W. M. and R. A. Bryson 1974. Dating Climatic Episodes of the Holocene. *Quaternary Research* 4:9-24.